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Sludge Combustor using Swirl and Active Combustion Control

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ABSTRACT

A research program directed at developing technology for compact shipboard incinerators for sludges is described. The concept utilizes previously developed Vortex Containment Combustor (VCC) as a primary unit with an active combustion control afterburner (AB).

The overall power scale of the combined system is 0.15 MJoule/sec and has a target sludge processing rate of 0.75 liter/min. Tests were undertaken to evaluate the particulate suspension qualities of the VCC and the overall performance of the combined VCC / active control AB processing intermediate levels of a surrogate 'sludge'.

The VCC operates like a combusting cyclone separator. Air is introduced circumferentially to create swirl in the combustion zone. This swirl suspends and traps particulate matter until it combusts or pyrolyzes to a size small enough to escape. Particle suspension was enhanced with flow directors that created a net upward velocity component near the floor of the VCC to prevent formation of dunes in the boundary layer. Particles were found to have very long residence times in the combustion zone of the VCC: 43 μm particles had a 1/e lifetime of over 20 seconds. The VCC was operated successfully both fuel lean and fuel rich. The VCC flame was found to be stable at a 'surrogate sludge' (water) flow rate of 0.35 liter/min. Tests at higher flow rates are pending.

In addition, mixing has been enhanced in a dump combustor configuration afterburner using active combustion control. The technology is based on injection of waste gases circumferentially into the shear layer of a central air jet from which sheds an acoustically controlled coherent spanwise vortex. The waste is rapidly entrained into the air vortex and the good large and fine scale mixing allows compact high efficiency combustion with high destruction and removal efficiency (DRE) and low emissions.

The performance of the combined system was evaluated with and without 'surrogate sludge'. It was found that the actively controlled AB efficiently combusts all of the pyrolysis gases and soot coming from the VCC: there was no visible soot emission and the carbon monoxide (CO) levels were below 50 ppm without sludge and below 70 ppm with a flow rate of 0.35 liter/min. In addition it was seen that the combined system efficiently destroys organics introduced into the 'surrogate sludge': the CO levels were virtually unchanged when 5% ethanol was added to the water 'surrogate sludge'. This implies greater than 99.9% destruction of the organic content in this yet to be optimized system.

INTRODUCTION

Fluid dynamics control performance in many practical combustion applications such as air breathing propulsion, energy conversion power plants, waste incinerators and other industrial burners. The importance of organized coherent large-scale vortical structures in large scale fluid mixing has been illustrated (1-3). Active manipulation of these vortical structures can lead to enhancement of the mixing process via an increase of the natural spreading rate of the shear layer. This can be realized using acoustic driving of the initial shear layer (4, 5). Through the use of advanced laser diagnostic

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techniques (6), the importance of controlling large and small scale mixing in combustion was determined (7). Active control by shear layer excitation has been used to enhance energy release (8-11) and to reduce emissions (12) and enhance hazardous waste incineration (13, 14).

At the Naval Air Warfare Center Weapons Division (NAWCWPNS), China Lake, work on active combustion control included open and closed loop control of small scale (~10kW) and large scale (~1MW) combustors to enhance their performance by increasing energy release, extending the lean flammability limit, and stabilizing the combustion (15). The focus of the investigations shifted to emphasize practical applications such as the investigation of techniques for the development of compact waste incinerators for use aboard Navy ships. The common underlying concept of the combustion processes discussed in the present paper is vortex combustion. The combustion in many practical burners is partially diffusion controlled and this means localized regions have fuel to air ratios not conducive to low emission performance. The vortex combustion technique ensures that the combustion is confined to regions (i.e., vortices) within the combustor where optimal local conditions can be maintained. The vortex provides intense mixing and long residence time necessary for a complete combustion process. The high strain rate in the vortex roll-up region also delays ignition until partial premixing is obtained. Thus vortex control, via acoustic excitation, can turn a sooty yellow benzene diffusion flame into a perfectly blue clean flame.

Recent work (16-21) emphasized the practical aspects of implementing active control vortex technology on an afterburner (AB) on a real incinerator. These included evaluating performance on more realistic waste surrogates, evaluating self excited (passive) configurations, looking at simplified designs, reducing back pressure, and quantifying performance at full scale (~1MW).

We have now initiated a Strategic Environmental Research and Develop Program (SERDP) funded program which addresses the thermal treatment of oil/water separator sludge. The program addresses the difficult problem of disposal of oily sludge from the wide variety of oil/water separators used in the military. These oily sludges which contain oil, water, and particulate matter have highly variable properties depending on their source of generation and must be disposed in an environmentally acceptable manner in compact equipment. The NAWCWPNS has teamed with GE Energy and Environmental Research Corporation to develop an advanced oil/water separator sludge thermal disposal system. The technology concept combines the features of a high performance Vortex Containment Combustor (VCC), which is an advanced unit ideal for low fuel value sludge, with an actively controlled afterburner, which is a direct outgrowth of studies sponsored by SERDP for the development of Compact, Closed-Loop Controlled Waste Incineration. As described in last years paper, the actively controlled afterburner is a dump combustor design with circumferential injection of pyrolysis gases into the roll-up region of a strong coherent axial vortex generated in the afterburner air flow. This greatly speeds mixing and leads to a compact afterburner with low emissions.

In this paper we will discuss preliminary results from a small scale unit combining the VCC with an properly scaled actively controlled afterburner. This is a 0.15 MJoule/sec unit with a target sludge throughput of 0.75 liter per minute. A companion paper (22) discusses a much larger VCC unit with a target sludge throughput of 3.2 liter per minute. The definition of 'full scale' depends on the application. If only the oily sludge from shipboard oil/water separators were the waste stream, then the small unit would be nearly full scale. However, if low duty cycle operation were required, or if gray and black water were processed, then the larger unit would be full scale.

The projected performance features of the actively controlled vortex containment combustor include the following: 1) compactness due to the high intensity VCC and compact afterburner, 2) flexibility and robustness for a wide range of sludge properties due to simple injection schemes, insensitivity of the combustion process and high combustion intensity, 3) very low NOx due to mixing features of the afterburner design (21), 4) automatic control using advanced active combustion control technology, 5)

very high destruction efficiency (>99.9999%) due to high performance VCC and active control afterburner, 6) very low carbon in ash due to long particle residence times in VCC burning zone which acts as an aerodynamic bottle to keep particles contained until they are completely combusted, 7) low particulate emissions due to centrifugal separation in VCC, 8) no organic (or dioxin) emissions due to high combustion efficiency and very low particulate emissions, 9) continual performance assurance due to continuous monitoring and active control, and 10) meeting all current and proposed IMO and land-based standards for sludge disposal.

EXPERIMENTAL

Figure 1 shows a side cross section of the VCC portion of the incinerator. The device has cylindrical symmetry so the combustion region, the central 356 mm outside diameter by 74 mm tall region, is circular. The actively controlled afterburner previously described (21) is adapted to the exhaust of the VCC.

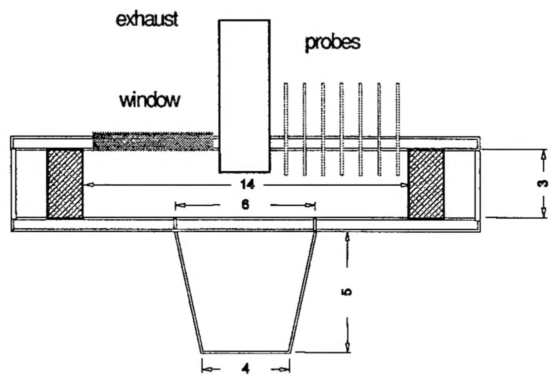

Fig. 1 VCC schematic configuration, side cross section. All dimensions shown are in inches. This is the small scale system for experimental investigation of parametric effects on performance.

The dimensions shown in Fig. 1 are for the experimental system fabricated for investigation of parametric variation of geometry and operating conditions on performance. The power level of this system is 55 kW to 170 kW depending on operating conditions. The power level of the full scale unit has not be decided upon pending a survey of sludge generation rates. The experimental unit was designed with optical access to assess the combustion region as well as allow laser diagnostic measurements on particulates in the flow. There is also provisions for introducing thermocouple or sampling probes at various radii in the combustion zone. The exhaust diameter was 65 mm down to 50 mm for some tests (the lower diameter greatly increases exit swirl at the expense of much larger pressure drop).

The VCC works by injecting the combustion air into the central circular combustion region circumferentially at a tangential angle to create swirl. One of the design parameters being studied is this air injection angle; all preliminary results shown here are for an injection angle of 45 degrees. The swirl acts like a centrifugal trap for particulates so that larger particles stay in the combustion "bubble" until they are reduced to a size small enough to move towards the center (22). The swirl flow and exhaust configuration creates a stagnation zone within the cone like bottom portion of the VCC where non-combustible particulates are trapped. There are, therefore, two separate particulate retention zones in the VCC design: one in the combustion zone and one in the particle trap

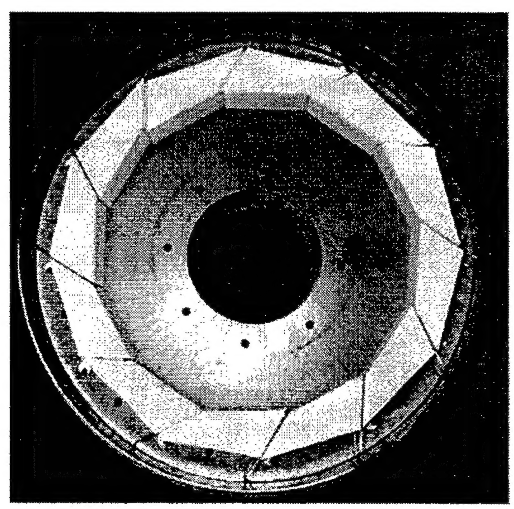

Fig. 2 Top internal view of VCC. Outside the white blocks is the air plenum. Inside is the swirling combustion zone.

below. Optimization of both will enhance the burnout of combustible particles and trap non-combustible particles, thereby leading to very low particulate emissions, and, therefore, low dioxin emissions. Any fine combustible particles that escape the VCC are combusted, along with the pyrolysis gases leaving the VCC, in the actively controlled afterburner.

Figure 2 is a top photo of the scale VCC. The swirl introduction wall was made from twelve ceramic foam blocks. The gap between the blocks is adjustable to allow parametric variation of the swirl introduction velocity. The baseline VCC air flow was 1000 liter/min. With the narrower gap of 0.81 mm the immediate swirl air injection velocity was 18.5 m/s. With the larger gap of 1.62 mm the nominal velocity was 9.3 m/s. The tangential velocity within the combustion zone was not directly measured; if one assumes the flow fills the chamber top to bottom and the same region radially then the average swirl velocity is 3.2 m/s. Obviously, the generation of swirl comes at a price of pressure loss. The pressure losses of the system were quantified under combusting conditions. Even with the narrow gaps (highest swirl level) the total pressure loss was only about 8 inches of water column. About half of this was the pressure drop between the air plenum and combustion zone and half due to the swirl (combustion chamber to exit).

The blocks are set for a 45 degree injection angle off tangent from a radius to the injection location. A separate set of blocks would be required for evaluating a different injection angle. Fuel and sludge surrogate were injected into the combustion zone from the top plate. In the companion paper (22) the fuel and sludge are injected circumferentially through the swirl injection wall.

Since the most difficult case for the sludge is no heating value, i.e. totally water, that is what was used as a surrogate sludge for the preliminary tests. Subsequent tests will first introduce combustible content to the water, by adding diesel or alcohol, and then introduce solids into the water as well. For the preliminary tests the fuel used was gaseous ethylene and the water injected via fogger nozzles similar to those used in desert locations for outdoor evaporative cooling.

Figure 3 shows a schematic diagram of the actively controlled afterburner (16-21). Briefly it consists of an acoustically forced central air jet of diameter 45.7 mm opening into a dump of diameter 210 mm and length 0.61 m. The pyrolysis gases from the VCC are introduced into the afterburner (AB) circumferentially around the central air jet via 16 equally spaced ejectors. Each ejector exit diameter was 9.5 mm diameter and the ejector nozzle a 6.35 mm OD tubing squashed into an elliptic jet (for enhanced ejector performance, ref. 23). Less than 10% of the total AB air was introduced via the ejectors. The AB central air jet average velocity was 20.8 m/s and this was acoustically modulated to create coherent span-wise vortices. The frequency of operation was in the 230 Hz range for a Strouhal number around 0.48.

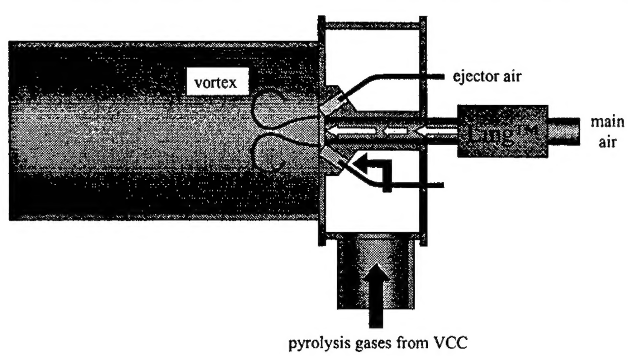

Fig. 3 Schematic diagram (not to scale) of actively controlled afterburner. The Ling™ is an acoustic driver that modulates the air velocity thereby actively creating a periodic coherent vortex in which the afterburner combustion occurs.

Emissions from the system were monitored with a water cooled rake probe and a Cosa™ 6000 stack gas analyzer (16-21).

RESULTS AND DISCUSSION

Effect of Swirl on the Afterburner

The output of the VCC is expected to have considerable residual swirl so the first aspect of the combined system tested was the effect of swirl on the actively controlled afterburner performance. Figure 4 shows that while swirl alone enhances mixing and reduces emissions (tracked here as CO), the active controller was not adversely affected by the swirl and was able to reduce emissions below that obtained with high swirl alone.

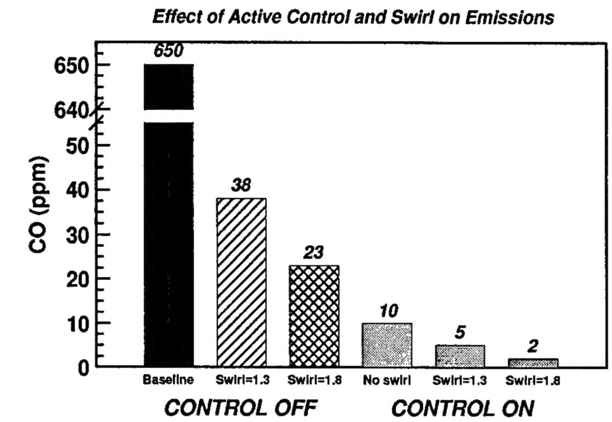

Fig. 4 The effect of swirl on the emissions from the actively controlled afterburner. The values listed for swirl are the ratio of the calculated swirl tangential velocity at the exit of the pyrolysis gas plenum to the main AB dump, to the main AB air jet average velocity.

However, it was found that the swirl created self excited acoustics in the AB and that could adversely affect closed loop active feedback control as the system will oscillate at it's own desired frequency and not allow external changes to a more optimum frequency. Figure 5 shows the frequency effects seen in these tests. As the swirl was increased the self oscillation intensity increased and the resonant frequency and mode changed. This might adversely affect an external controller ability to drive the system. However, the results of Figs. 4 and 5 were obtained from a prior AB design that did not have ejectors as shown in Fig. 3. Instead the pyrolysis gas plenum just exited into the AB vortex region via an annular slot. The flow straightening nature of the ejector ports of the current design are expected to significantly reduce the effect of swirl entering via the VCC output. Indeed, in combined VCC / AB tests described below, there was no effect of swirl in the AB and no self excitation of the AB.

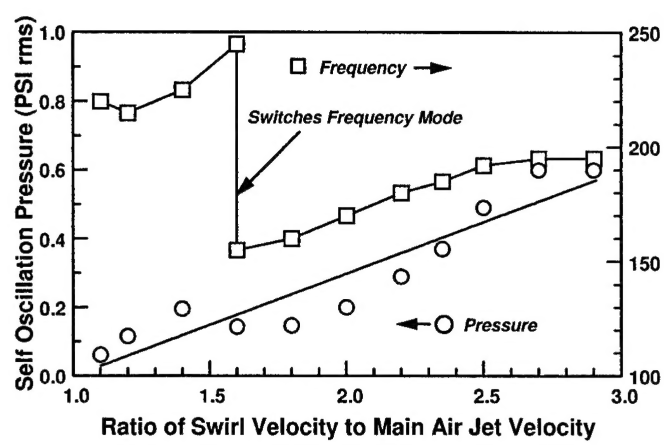

Fig. 5 Effect of swirl on active control of afterburner.

Fuel Rich Operation of the VCC

The original EERC work was done fuel lean in the VCC. If we decide to adapt the VCC to our previously designed AB then the VCC would, of course, have to be run significantly fuel rich to provide for combustibles in the AB. Since the air flow of the VCC defines the swirl and particulate suspension, we kept that constant and increased the fuel flow rate to up the stoichiometry. We were able to operate the scale VCC successfully over a stoichiometry range of 0.8 to 2.5. Figure 6 shows that as the stoichiometry is increased the flame moves from tighter radii towards the swirl injection wall at larger radii. At the highest stoichiometry the VCC emitted large quantities of soot. In

subsequent tests with the AB adapted to the VCC no visible soot was emitted; it is all consumed in the AB.

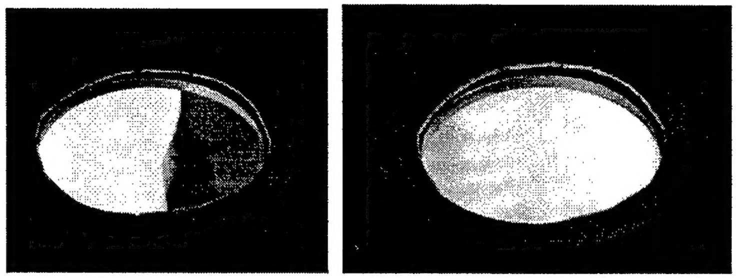

Fig. 6 View into the combustion zone of VCC through quartz window. The left image was taken for a stoichiometry of 0.8 (i.e. fuel lean) while the right is for 2.5 (fuel rich). The left side of each image is towards the centerline of the VCC.

VCC Particle Trapping for Large Particles

The original EERC VCC was designed to burn finely pulverized coal, but we do not anticipate being able to atomize the sludge to small particles, so it was necessary to evaluate the performance of the VCC for larger particles. Particles of various size and density were tested in the experimental VCC under cold flow conditions. The particles used were those that were readily available and included non-fat dry milk at a density of about 1.4 gm/cm^3 as well as baking soda at 2.2 gm/cm^3, sand at 2.65 gm/cm^3 and talc at 2.75 gm/cm^3. Obviously in real sludge tests the particles would have significant organic content and densities that were near water or lower, but we wished to use particles that would not evaporate and were dry. Since real sludge would also contain some high density particles (dirt) the tests with sand (a relatively coarse particle) and talc (fine particles) were relevant. The particles were sieved to the desired size. The particles were injected from a transient fluidized bed. A burst diaphragm of aluminum foil was placed upstream of the particle injection tube. This tube entered what would be the combustion zone of the VCC (these tests were cold flow) and turned 90 degrees so that the particles were ejected with a velocity in the plane of the VCC. We investigated the direction of particle injection, but the best seemed to be along the swirl flow direction (i.e. along a tangent). Particles were followed using a diode laser (670 nm) and collection of right angle Mie scattering using a filtered photo-diode. This system monitored the particles through the quartz windows. It was mounted on a stepper motor slide stage to map out radial profiles. The window allowed reaching all the way to the wall by slightly canting the angle of the optical system.

It was found that larger particles fell to the floor of the VCC and formed dunes. It was thought that these would burn slowly in the boundary layer. It was calculated (via particle settling velocities) that dry milk particles bigger than 50 μm would not even make a single turn around the VCC before hitting the floor. Particles larger than 200 μm would not even complete 25 degrees before hitting the floor. Therefore the internal height of the swirl zone was reduced to 48 mm by adding a bottom plate that was 25 mm thick. This increased the swirl level by reducing the cross-sectional area for swirl flow. The area was reduced by about 35%. Ramps were machined into the bottom plate that intercepted each of the swirl air introduction slots (Fig. 7). A portion of the incoming swirl air was in this way deflected in the up direction giving an upward velocity vector to the air flow to counter the settling velocity of the particles. This modification was found to greatly reduce the accumulation of particles

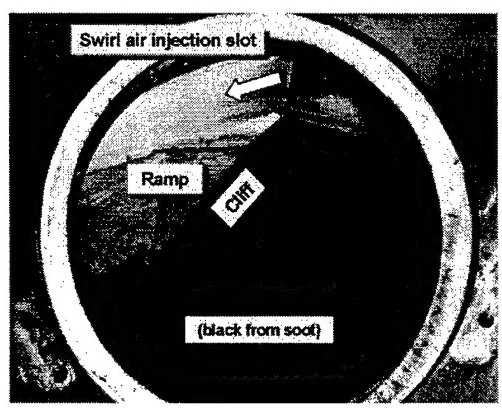

Fig. 7. Looking into the combustion zone of the VCC through the window port at the base plate with swirl flow deflection ramp. The white arrow shows where the swirl air flow exits the slot in the outer wall.

on the floor and enhance dispersion within the combustion region. The dunes no longer formed as particles that did manage to make it to the floor were re-injected into the flow when they fell off the 'cliffs' shown in Fig. 7 into the upward directed portion of the swirl flow. All subsequent results presented here are for this configuration.

With the problem of particle settling solved we continued to quantify particle retention times and suspension locations. Figure 8 shows the particle radial distribution and retention time, within the combustion region, for particles of density 1.4 gm/cm^3 and diameter of about 60 μm or below. Note that the particles group near the outsize diameter of the combustion zone and that the retention time is quite long. These particles would be trapped in the combustion zone for a very long time insuring good burnout.

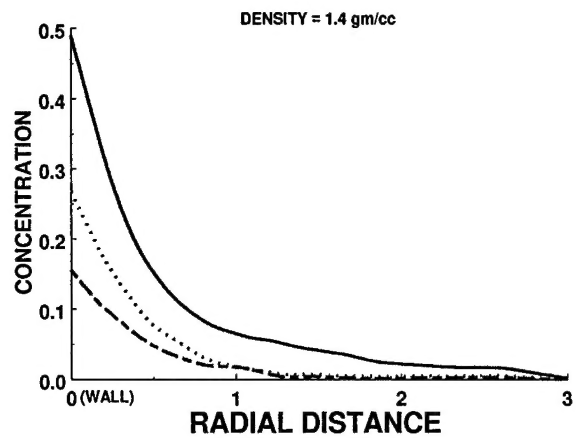

Fig. 8 Radial distribution of particles, measured via laser light scattering, as a function of time after injection. The top curve is a time 0, the second down at 1 minute, and the third at 2 minutes. The horizontal axis is inches. The dry milk particles were sieved to around 60 μm or below.

Figure 9 shows particle retention times for various density and sized particles. As expected larger particles are trapped for longer times (the concentration decays slower). This can be seen in Fig. 9 by comparing the triangles (150 μm) with the circles (60 μm) for baking soda (2.2 gm/cm^3. Also, denser particles are trapped longer than lighter ones as can be seen from comparing the circles (2.2 gm/cm^3) with the diamonds (same size, 1.4 gm/cm^3). The squares are for talc which although sieved to 60 μm is actually considerably smaller, and therefore has a shorter retention time. Microscopic analysis of these particles showed an average diameter of 13 μm and a d_{43} of about 43 μm. Even these small particles had a 1/e retention time of about 20 seconds in the scale VCC. Unfortunately we did not have access to sieves or low density particles considerably smaller than 60 μm.

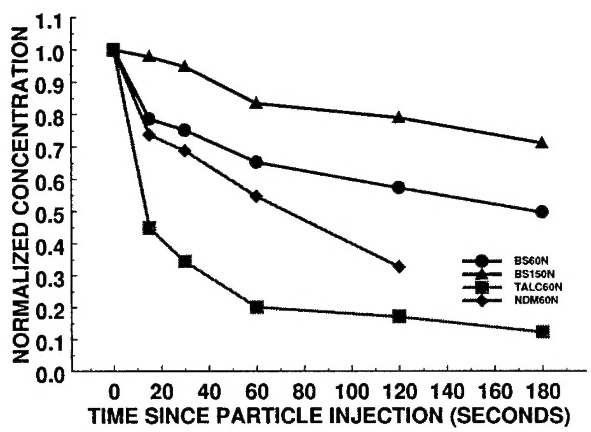

Fig. 9 Particle retention time plots for various particles measured 6 mm from the wall. Triangles are for 150 μm particles of density 2.2 gm/cm^3, circles for 60 μm particles of 2.2 gm/cm^3, squares for <<60 μm particles of 2.75 gm/cm^3, and diamonds for 60 μm particles of 1.4 gm/cm^3.

Integration of VCC and AB

Since we were convinced by the particulate tests that the VCC particle suspension and trapping was adequate, we adapted the output of the VCC to the input of a properly scaled version of our actively controlled afterburner (AB). We wished to evaluate the performance of the VCC alone, operated fuel lean, and the VCC + AB. We suspected that while the VCC alone suspends particulate matter for long burn out times the gas mixing might not be ideal leading to emissions. In combined tests the

VCC was operated fuel rich ($\Phi = 2.5$) so that there would be combustibles left for proper operation of the AB. The AB has no auxiliary fuel input; it works solely off the residual combustibles from the VCC. Table I shows the operating parameters, and performance, of the VCC alone versus the VCC + AB. These tests were without sludge or any sludge surrogate, like water. We wished to evaluate the baseline capabilities of the system alone. Clearly, if the no-sludge operation has higher than allowable emissions, adding sludge will not improve the performance.

Table I Performance of VCC alone compared with VCC + AB with and without active control. The fuel is ethylene and the units are liters per minute.

	VCC Air	Fuel	AB Air	VCC kW	AB kW	CO ppm
VCC only at $\Phi = 0.7$	800 l/m	39 l/m	-	39	-	481
VCC at $\Phi = 2.5$ + AB No Control	800 l/m	140 l/m	1940 l/m	55	82	870
VCC at $\Phi = 2.5$ + AB With Control	800 l/m	140 l/m	1940 l/m	55	82	47

It is clear from Table I that the AB substantially improves the performance of the system over the VCC alone: the CO was reduced by a factor of ten. This was despite the heavy soot load from the VCC when operated fuel rich: there were no visible soot emissions from the AB. So the VCC / active AB combination is a good one: the VCC suspends particulate matter and insures its gasification while the AB completes the combustion of the resulting pyrolysis gases and fine particulate (soot) in a high mixing rate high combustion intensity environment for low emissions. This improvement is obtained, of course, at the expense of quite a bit of extra fuel.

Performance with Surrogate 'Sludge'

As mentioned in the experimental section, we decided to start with simple sludge 'surrogates' to evaluate the system performance with sludge of nearly zero heating value. So we used either pure water or water with 5% by volume of ethanol. Ethanol was chosen to include some form of combustible material in the 'surrogate sludge' while not requiring constant stirring of non-miscible components. The ethanol was added to the water to evaluate destruction of organics introduced via the sludge input. We wanted to make sure that there was no cold escape path from sludge input to system output. The 'surrogate sludge' tests were done only on the combined VCC / AB system so the destruction location, VCC or AB, for the organics added via the sludge input is unknown. As mentioned in the experimental section the 'surrogate sludge' was introduced via swirl based fogger nozzles. These probably produce very fine droplets which enhances evaporation within the VCC. Real sludge would not pass through these nozzles. Sludge nozzle technology evaluations are discussed in the companion paper (22).

The combined VCC / active AB was operated with a 'surrogate sludge' rate of 0.35 liter/min introduced into the VCC. The VCC and AB flames were still stable at this flow rate. Higher flow rates have not yet been investigated. Figure 10 shows the performance of the combined VCC / active AB as a function of the forcing frequency for the AB main air flow with and without water flow (at 0.35 liter/min). This normally optimizes at a given frequency that is equal or near to the preferred mode of the AB air jet. The system optimizes at approximately 230 Hz which is a Strouhal number of 0.48. Also indicated in Fig. 10 is the performance level of the VCC alone, operated fuel lean. It can be seen from Fig. 10 that the performance of the system is slightly worse with the 0.35 liter/min water flow present: the minimum CO without water flow is 47 ppm and with water it is 69 ppm.

Understandably, the NOx is much lower with water injection, 7 ppm vs. 40 ppm, as the water drops the gas temperature: the measured pyrolysis gas temperature input to the AB was 555 °C without water and 422 °C with.

However, another disturbing effect comes from water injection: the optimal frequency of the AB control forcing is changed. We do not know why this occurs. It is possible that with high water content the AB flame is further downstream; indeed it looked to be. The combustion would then be occurring in a region where the vortex had grown bigger. Forcing at a higher frequency would make slightly smaller starting vortices and possibly recover the same size vortex at the further downstream location of the combustion with water vs. without. Nevertheless, the important aspect is that the frequency dependence on feed conditions might necessitate the use of a adaptive controller.

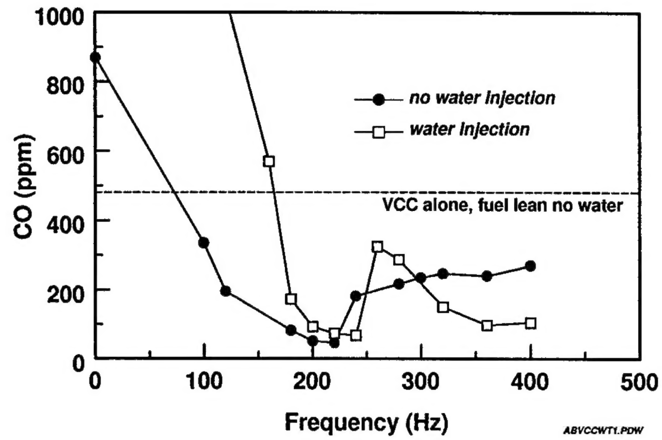

Fig. 10 Performance of the VCC / active AB combination with and without 'surrogate sludge', i.e. water, injection. The water flow rate was 0.35 liter/min. The abscissa is the frequency of operation of the active controller, i.e. the frequency of vortex shedding driven in the AB main air flow.

Figure 11 also shows controller operational differences caused by 'surrogate sludge' injection: the intensity of forcing required for a given performance level was increased. The high water content combustion in the AB apparently requires even stronger more coherent vortices to give the same mixing and low emissions as when water is present at lower levels. We do not think that the temperature of the AB input gases is the controlling parameter: prior work has shown good performance of the actively controlled AB even with room temperature gas input.

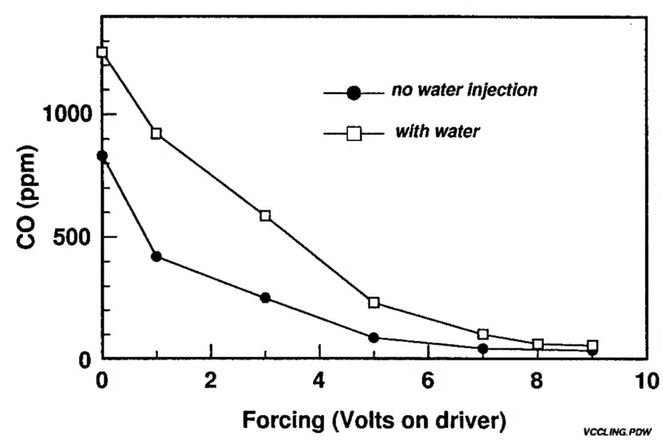

Fig. 11 Performance of the combined VCC / AB with and without 'surrogate sludge' injection as a function of active control intensity (the RMS volts to the acoustic driver).

Figure 12 shows that the optimum overall system stoichiometry was not strongly affected by 'surrogate sludge' injection. The water flow rate of 0.35 liter/min is the maximum studied to date but it is only about one half of the design point (22) which is set for a VCC gas temperature of at least 1000 °C. Work in the immediate future will be to evaluate performance at elevated 'surrogate sludge' flows.

Finally, to judge the fate of organics in the 'surrogate sludge', ethanol was added to the water (at 5% by volume). Figure 13 shows how this affected the performance of the VCC / AB combination. There were no substantial changes. The differences in CO level at the optimum control conditions was within the resolution of the monitoring instrument (1 ppm). If we assume the variability of the monitoring instrument was 5 ppm, and we assume that unburned ethanol is converted all to CO,

then the minimum combustion efficiency of the ethanol in the water was 99.90% (our monitor saw no differences in unburned hydrocarbons but its resolution is only 0.01%). The system was re-optimized for stoichiometry, but the best conditions with ethanol injection (vs. pure water) turned out to be the same ethylene fuel flow and a somewhat lower overall fuel to air ratio (due to the ethanol). The NOx went up: with pure water it was 7 ppm and with the 5% ethanol test it was 20 ppm. The increase was no doubt due to the slight increase in stoichiometry.

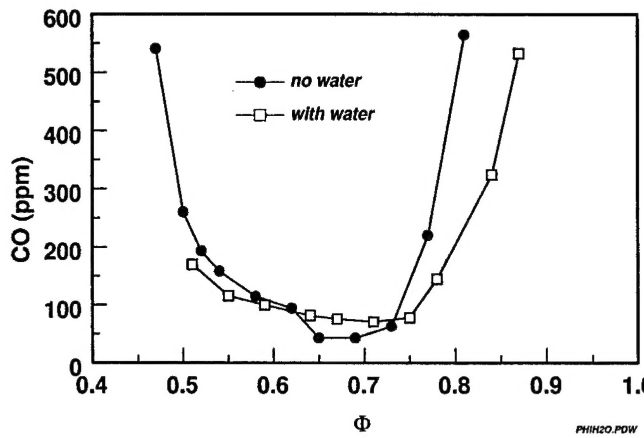

Fig. 12 Effect of water addition to the VCC / AB system stoichiometric optimization. Φ is the overall fuel to air stoichiometry of the combined system.

SUMMARY

A sludge incineration technology has been assembled from a Vortex Confinement Combustor (VCC) based primary unit coupled to an actively controlled annular dump combustor afterburner (AB). The overall power scale of the combined system is 0.15 MJoule/sec and has a target sludge processing rate of 0.75 liter/min. Tests were undertaken to evaluate the particulate suspension qualities of the VCC and the overall performance of the combined VCC / active control AB processing intermediately levels of a surrogate 'sludge'.

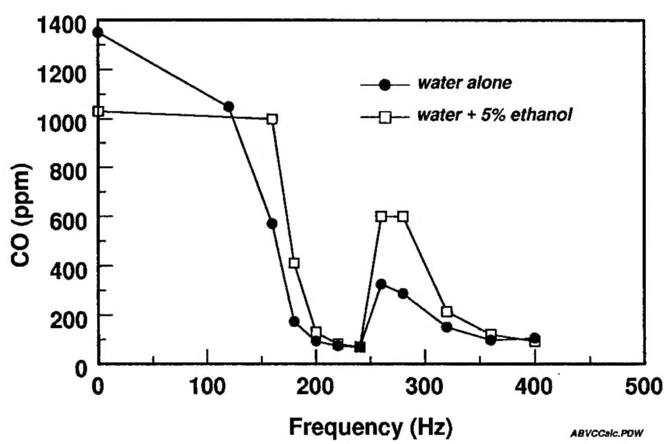

Fig. 13 Effect of organics in the 'surrogate sludge' on performance of the VCC / AB system.

The VCC operates like a combusting cyclone separator. Air is introduced circumferentially to create swirl in the combustion zone. This swirl suspends and traps particulate matter until it combusts or pyrolyzes to a size small enough to escape. Particle suspension was enhanced with flow directors that created a net upward velocity component near the floor of the VCC to prevent formation of dunes in the boundary layer. Particles were found to have very long residence times in the combustion zone of the VCC: even 43 μm particles had a 1/e lifetime of over 20 seconds. The VCC was operated successfully both fuel lean and fuel rich. The VCC flame was found to be stable at a 'surrogate sludge' (water) flow rate of 0.35 liter/min. Tests at higher flow rates are pending.

In addition, mixing has been enhanced in a dump combustor configuration afterburner using active combustion control. The technology is based on injection of waste gases circumferentially into the shear layer of a central air jet from which sheds an acoustically controlled coherent spanwise vortex. The waste is rapidly entrained into the air vortex and the good large and fine scale mixing allows compact high efficiency combustion with high destruction and removal efficiency (DRE) and low emissions.

The performance of the combined system was evaluated with and without 'surrogate sludge'. It was found that the actively controlled AB efficiently combusts all of the pyrolysis gases and soot coming from the VCC: there was no visible soot emission and the CO levels were below 50 ppm without sludge and below 70 ppm with a flow rate of 0.35 liter/min. In addition it was seen that the combined system efficiently destroys organics introduced into the 'surrogate sludge': the CO levels were virtually unchanged when 5% ethanol was added to the water 'surrogate sludge'. This implies greater than 99.9% destruction of the organic content in this yet to be optimized system.

Future work will be addressed at 1) increasing the 'sludge' flow rate to the design point, 2) introducing diesel oil into the sludge component, 3) firing the VCC on diesel oil, and 4) including some solids in the sludge.

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